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Evolution of lightning and the possible initiation/triggering of lightning discharges by the lower positive charge center in an isolated thundercloud in the tropics

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[1] The evolution of lightning and the shape of recovery curves after multiple-discharge flashes in a thundercloud have been studied from the surface measurements of electric field and Maxwell current near a tropical thundercloud. Observations suggest a tripole structure of the cloud and that its lower positive charge center (LPCC) plays a dominant role in initiating/triggering an intracloud (IC) or cloud-to-ground (CG) lightning discharge. IC discharges in the initial stage of thundercloud are followed by CG discharges from the LPCC and then by two distinct groups of multiple-discharge flashes. Each flash in the first group consists of an IC discharge triggered by a CG discharge and in the second group a CG discharge triggered by an IC discharge. Flashes in each group are bunched together for ~15–20 min and occur with almost a regular periodicity of 1–1.5 min. The Maxwell current during every such flash in both groups has a bipolar transient and a positive overshoot that subsequently relaxes back to its predischarge value. The magnitudes of overshoot for the flashes in the first group are found to be much lower than those for the flashes in the second group. From a small portion of the recovery curves of such multiple-discharge flashes, one can conclude that the rate of charge buildup in the main negative charge center is higher than that in the LPCC. *INDEX TERMS:* 0320 Atmospheric Composition and Structure: Cloud physics and chemistry; 3304 Meteorology and Atmospheric Dynamics: Atmospheric electricity; 3324 Meteorology and Atmospheric Dynamics: Lightning; *KEYWORDS:* evolution of lightning, shape of recovery curves, mutiple-discharge flashes

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1. Introduction

[2] The electrical structure of thunderstorms is generally represented by an electrical dipole with positive charge appearing in the upper portions of the storm and negative charge below it. In addition, a region of positive charge is often reported to exist in the bases of thunderstorms. Early balloon-borne measurements of electric field within cloud by *Simpson and Scrase* [1937] and *Simpson and Robinson* [1941], and more recent aircraft or balloon-borne measurements of precipitation particle charges by *MacCready and Proudfit* [1965], *Holden et al.* [1983], *Marshall and Winn* [1982], *Marshall and Stolzenburg* [1998], *Bateman et al.* [1999], and *Mo et al.* [2002] show the existence of the lower positive charge center (LPCC). From a summary of past investigations on the polarity of thunderclouds, *Williams* [1989] concludes that several earlier measurements tend to confirm the tripole structure with different emphasis given to the LPCC and that an electrical tripole is a more accurate representation of thundercloud structure. However, from the vertical profiles of electric field obtained from balloon-borne soundings through storms, *Marshall and Rust* [1991], *Rust and Marshall* [1996] and *Stolzenburg et al.* [1998] infer that the electrical structure of thunderstorms may be more complex than a simple dipole or tripole. They infer from their observations that within convective charge regions, the basic charge structure has four charge regions, alternating in polarity, and the lowest is a positive charge region. Outside updraft regions, they infer six or even more charge regions, the lowest one being again a positive charge region. However, recent three-dimensional lightning mapping observations of *Coleman et al.* [2003] show that lightning appears to deposit charge of opposite polarity in relatively localized volumes of preexisting lower positive, midlevel negative and upper negative charge regions. These observations, thus reconcile the complex charge structures inferred from balloon soundings and the simpler structures inferred from lightning measurements.

[3] *Clarence and Malan* [1957] suggested that lower positive charge is essential for the initiation of the cloud-to-ground (CG) lightning. Several observations made in the past support the idea that the lower positive charge actively participates in CG lightning. *Williams* [1989] investigated the problem by computing field changes in a hypothetical four-station field measurement network set-up at the ground

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when both main negative charge and a smaller quantity of lower positive charge from a charge distribution above the network are lowered by a CG lightning. On the basis of his calculations, Williams discusses the estimated errors that might have resulted in some earlier studies [e.g., *Krehbiel et al.*, 1979; *Krehbiel*, 1986; *Jacobson and Krider*, 1976] if the effect of lower positive charge is not considered. Further, from the consideration of the vertical distribution of the gravitational power associated with falling precipitation in thunderclouds, *Williams* [1989] suggests to associate intra-cloud (IC) lightning with convection and the upper positive dipole and CG lightning with sedimentation and the lower negative dipole.

[4] Although most CG discharges are known to transfer negative charge to the ground, observations of *Brook et al.* [1982, 1989], *Rust et al.* [1981], *Rust* [1986], and *Baral Mackerras* [1993], and *Stolzenburg* [1994] confirm that the occurrence of +CG discharges, transferring positive charge to the ground is not uncommon. Two hypotheses are generally postulated to explain the occurrence of +CG lightning. In one hypothesis, the thundercloud is considered as a sheared positive dipole and +CG lightning takes place between the upper positive charge of the positive dipole and the ground at the downwind and down-shear positions of the deep convection [*Pierce*, 1955; *Brook et al.*, 1982; *Takagi et al.*, 1986]. However, it is difficult to explain the large displacements of $\sim$100 km that are often reported in bipole patterns [*Orville et al.*, 1988; *Engholm et al.*, 1990]. In the second hypothesis, the thundercloud is considered as an inverted dipole [*Orville and Berger*, 1973; *Hubert et al.*, 1984] but has problems explaining the observed scarcity of positive lightning associated with localized deep convection [*Williams*, 1989]. Evidence of the inverted polarity electrical signatures in convective regions of thunderstorms is recently reported by *Rust and MacGorman* [2002]. The extensive layers of positive charge near the cloud base have also been reported in the thunderstorms that occur over the Tibetan Plateau [*Qie et al.*, 1999, 2003].

[5] The coronae space charge introduced from ground into the sub-cloud layer below thunderstorms is known to strongly influence the shape of recovery curves at the ground surface [e.g., *Standler and Winn*, 1979; *Soula and Chauzy*, 1991]. In an earlier study we reported the shape of recovery curves of +CG flashes occurring from the LPCC of an overhead thunderstorm [*Pawar and Kamra*, 2002]. Here, we report our surface measurements of electric field and Maxwell current near a tropical thundercloud and study the evolution of lightning with time and the change in the shape of field recovery curves of lightning through the life history of the thundercloud. We also investigate from our data the role of the LPCC in initiating/triggering a lightning discharge.

2. Instrumentation

[6] Measurements of the electric field and Maxwell current were made at the Atmospheric Electricity Observatory, Pune (18°32′N, 73°51′E). Electric field was measured with an a.c. field mill with its sensors kept flush with the ground. It can measure electric field of ±12.5 kV m^{-1} and has a response time of 0.1 ms. The Maxwell current sensor was similar to that of *Krider and Blakeslee* [1985] and *Deaver and Krider* [1991] and consisted of a 1 m^2 flat aluminium plate mounted flush with the ground on four porcelain insulators fixed in a pit. Its output was fed to an electrometer circuit consisting of an operational amplifier (311 K) and a resistance of 10^9 Ω in parallel with a capacitance of 100 pF. It can measure ±5 nA m^{-2} and has a response time of 0.1 s. The signals from both sensors were amplified and fed through coaxial cables to a data logger system, which digitized the analog signals using a 12-bit analog-to-digital converter for the recording and storage at a frequency of 10 Hz.

[7] Both the field mill and the Maxwell current sensor were cleaned and their zero-levels were checked before measurements were made below a storm. No appreciable zero-shift was found with time except when it rained heavily during measurements. The measurements on such occasions were discontinued and the data collected during such periods were not considered. No rain was reported at the observatory during the period of this thundercloud.

[8] Dry- and wet-bulb temperatures, wind speed and direction and rainfall at the observatory were measured with a weather station and recorded and stored in another data logger at a rate of 1 sample per minute.

3. Sign Convention and the Criteria for Differentiating Between IC and CG Flashes

[9] We have followed the convention that the fair-weather electric field and the associated conduction current carrying positive charge downward to the ground are of negative polarity. Further, a positive field change causes the positive displacement current and a negative field change causes the negative displacement current.

[10] We have used the criteria of *Deaver and Krider* [1991], i.e., a CG discharge causes an overshoot and an IC discharge causes an off-set above noise level in the Maxwell current density, to differentiate between the IC and CG lightning discharges (e.g., see the changes associated with IC and CG discharges in Figure 2 to be described in section 5). In our observations too, as observed by *Krider and Blakeslee* [1985] below active thunderstorms, the Maxwell current densities are about an order of magnitude larger than those reported by *Deaver and Krider* [1991]. In case of −CG flashes, the overshoot in Maxwell current is positive, as observed by *Deaver and Krider* [1991]. However, in case of +CG flashes, the overshoot in Maxwell current is negative. In both cases, however, the Maxwell current subsequently relaxes back to its preflash level (examples of the overshoots associated with +CG and −CG flashes can be seen in Figures 3 and 4, respectively, to be described in section 5).

4. Observations

[11] An isolated convective cloud developed northeast of our observatory on the afternoon of 3 May 2003. Its horizontal distance from the observatory, as estimated from the time-to-thunder technique, during several lightning flashes, was $\sim$5 km. Winds were almost calm or low. Visual observation showed that the cloud remained almost stationary during its lifetime and its vertical depth was far greater than its horizontal width in the initial and mature stages. The development of isolated thunderclouds in this area in the

premonsoon season is generally due to instability of the lower atmosphere created by the convergence near the ridgeline due to the high-pressure areas over the Bay of Bengal and Arabian Sea regions. Base heights of these thunderclouds are generally 1 to 2 km. These convective clouds are electrically active and exhibit considerable lightning activity. On this day, the dry-bulb temperature at the observatory dropped from 31.3°C at 1550 h to 23.6°C at 1620 h i.e., a drop of 7.7°C in ~30 min. Wind speed decreased and changed direction from the prevailing southwesterly to northeasterly from 1640 to 1710 h. These features are not much different from those of a typical thunderstorm in this region. The size of this cloud and the lightning frequency in it significantly increased after 1655 h. Recovery curves of lightning flashes exhibited atypical shapes and showed a systematic change with time as the storm evolved and therefore prompted us to further analyze the data.

[12] The field mill was turned on at 1635 h and the Maxwell current sensor at 1644 h when the cloud had just started to grow. Our observations indicate the presence of a widespread region of large positive charge or a combination of several positive charge regions in the lower portions of the thundercloud. Figure 1 shows the record of the surface electric field and Maxwell current at our observatory during the period of storm. The initial 2–3 min field record is not reliable because of some initial adjustments of the equipment. Each stage marked in the electric-field record in Figure 1 is separated from the subsequent one by a transition period (TP). These different stages and transition periods will be further discussed in the subsequent sections. Comparatively large values of the positive electric field in the initial and near dissipating stages of thunderstorms are most probably produced because of the dominant effect of the main negative charge center of the thundercloud when the effect of the LPCC and other positive charge regions is weak. The electric field remained negative for most of the duration (~80 min) in between these initial and final periods except for some short excursions to positive values associated with lightning discharges. Observations of such extensive regions of positive charge in the lower portions of thunderstorms that occur over Alibag (~100 km from the present site) in premonsoon seasons (May–June) are reported in early measurements of *Banerji* [1930, 1932]. Earlier observations of *Pawar and Kamra* [2002] also show the presence of a strong and extensive LPCC in a similar thunderstorm at this station. Although our measurements could not be continued beyond 1844 h because of power failure, the reversal of electric field after 1825 h is likely to be due to the end-of-storm oscillation (EOSO) as the storm was visually observed to dissipate at about 1900 h [*Moore and Vonnegut*, 1977]. Although the EOSOs observed by us at this station generally follow the pattern as suggested by *Moore and Vonnegut* [1977] (see, for example, *Pawar and Kamra* [2002]), the exact periods of field reversals to opposite polarities could not be established in case of this thunderstorm. The changeover of electric field to the fair-weather polarity after ~1830 h, however definitely shows the presence of a net positive charge above.

5. Evolution of Lightning

[13] Our observations show a very systematic change in the nature of lightning flashes and the shape of their recovery curves with the passage of time throughout the life history of thunderstorm. The whole thunderstorm period can be divided into five different stages, marked in Figure 1.

5.1. Stage A

[14] In the initial stage of thunderstorm when the field is mostly positive there is hardly any lightning activity. A few IC flashes that occur during this period (e.g., at 16:46:04, 16:50:48, 16:50:55, 16:52:06, etc.) show destruction of negative charge above and probably occur between the main positive and negative charge centers of the thundercloud. The first lightning discharge, as detected by a step-change on an expanded timescale field record, occurred at 16:46:04 h. Recovery curves of these flashes when seen on an expanded timescale are of the exponential type generally observed for such intracloud discharges.

5.2. Stage B

[15] It is likely that the change in polarity of the electric field from positive to negative was caused by the development of a strong LPCC that dominated the electric field at the ground, though we cannot rule out the possibility that the main positive charge center (or a combination of several positive charge regions) is dominating the electric field at the ground. Observations of strong negative values of the before-discharge electric fields, their occasional excursions to positive values after the discharge, and the field's quick recovery to the before-discharge values combine to indicate that charges in the LPCC and the main negative charge center are probably participating in some discharges. The field changes associated with most flashes that occur during this period, especially between 1716 to 1747 h show destruction of positive charge above, possibly in the LPCC. However, we cannot rule out the possibility of some field changes being associated with discharges occurring in the main positive and negative charge centers of the cloud or in a storm beyond reversal distance. Figure 2 shows a typical record on an expanded timescale showing the electric field and Maxwell current changes during some IC and CG flashes during this period. Out of ~82 flashes that occur during this period, at least 15 flashes show overshoots in the Maxwell current density. These overshoots, such as the one observed in the case of CG flash in Figure 2, are above noise level in the Maxwell current records. However, since CG flashes are positive in this case, the overshoots, as expected, are negative, i.e., opposite in polarity to that of *Deaver and Krider*'s [1991] case. Line noise of 60 Hz was not found to interfere with our observations.

5.3. Stage C

[16] The shape of the recovery curves of the flashes occurring after 1753 h in Figure 1 is distinctly different and is discussed below with a possible interpretation discussed in sections 8 and 9. In these flashes, a positive field change showing destruction of positive charge above is immediately followed by a comparatively smaller negative field change showing destruction of negative charge above, with approximately same rate of field change. Figure 3 shows a record of the electric field and Maxwell current on

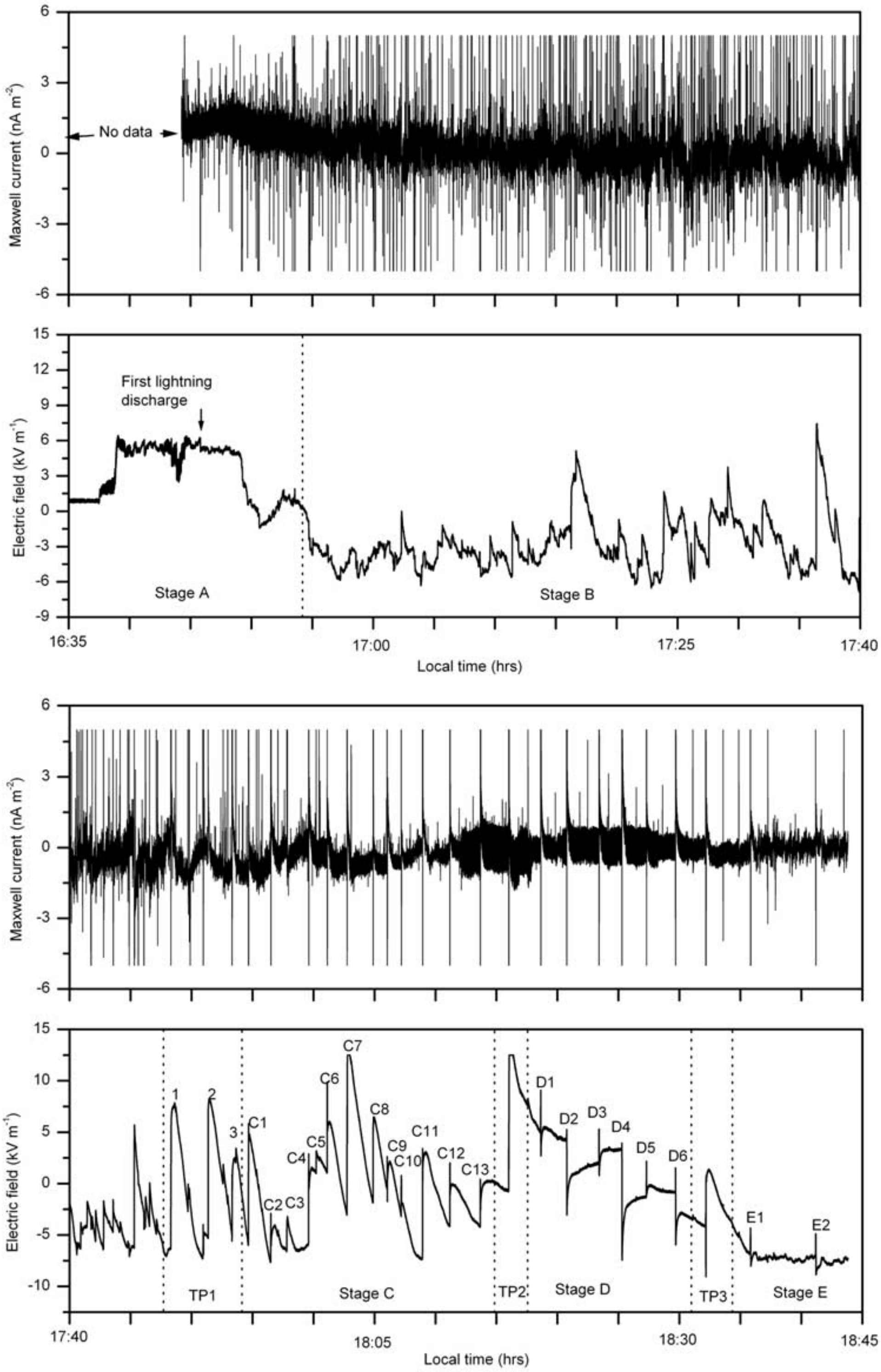

Figure 1. Record of the surface electric field and Maxwell current density during the period of the thunderstorm on 3 May 2002. The record has been divided into stages A, B, C, D, and E, which are separated from each other by transition periods (TPs); C and D indicate the field changes associated with different flashes in stages C and D, respectively.

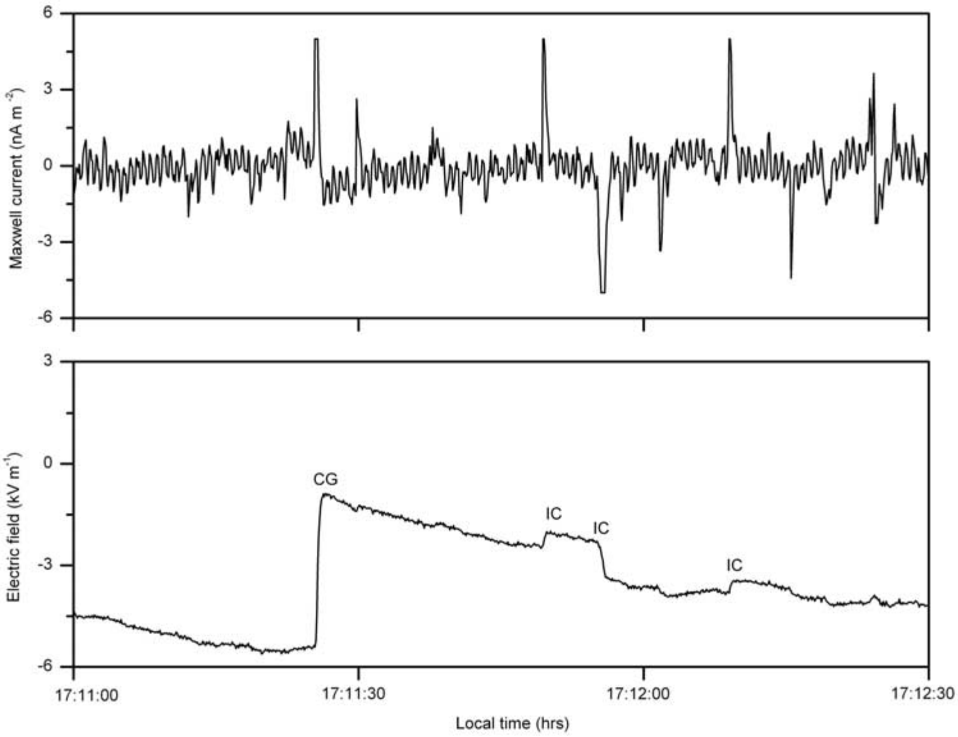

Figure 2. Electric field and Maxwell current changes on an expanded timescale during stage B. The overshoot in Maxwell current for CG discharge is above noise level.

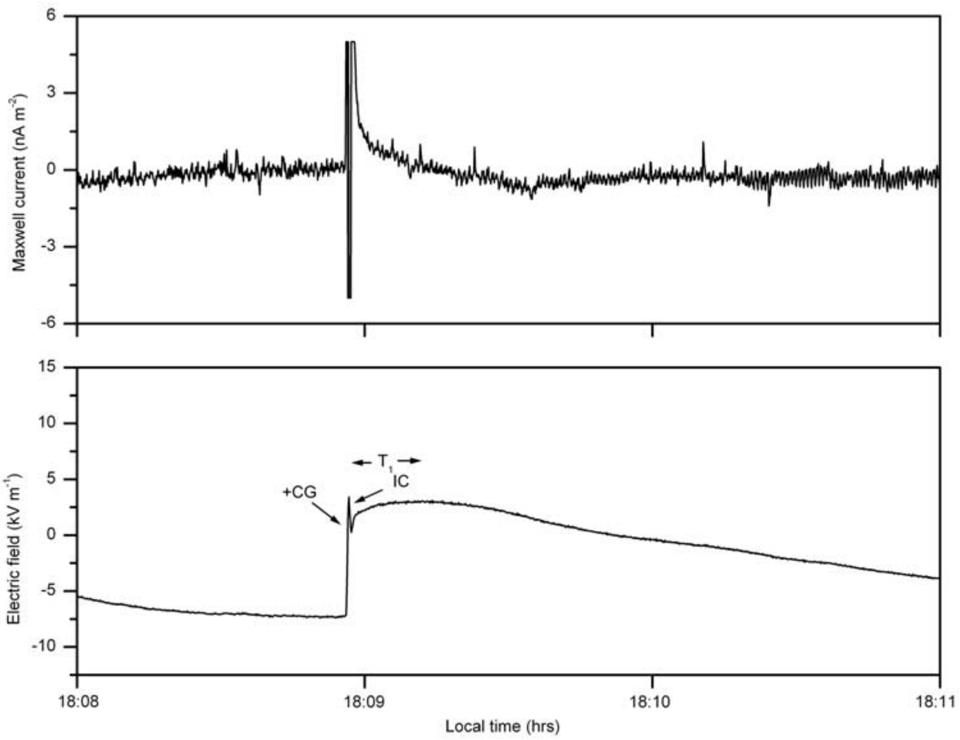

Figure 3. Electric field and Maxwell current changes on an expanded timescale during a typical flash in stage C. During a flash in this stage, a +CG discharge from the LPCC causing a positive field change probably triggers an IC discharge between the LPCC and the main negative charge of the thundercloud and causes a negative field change. During the time period T1 the electric field increases, and the Maxwell current decays back to its predischarge level.

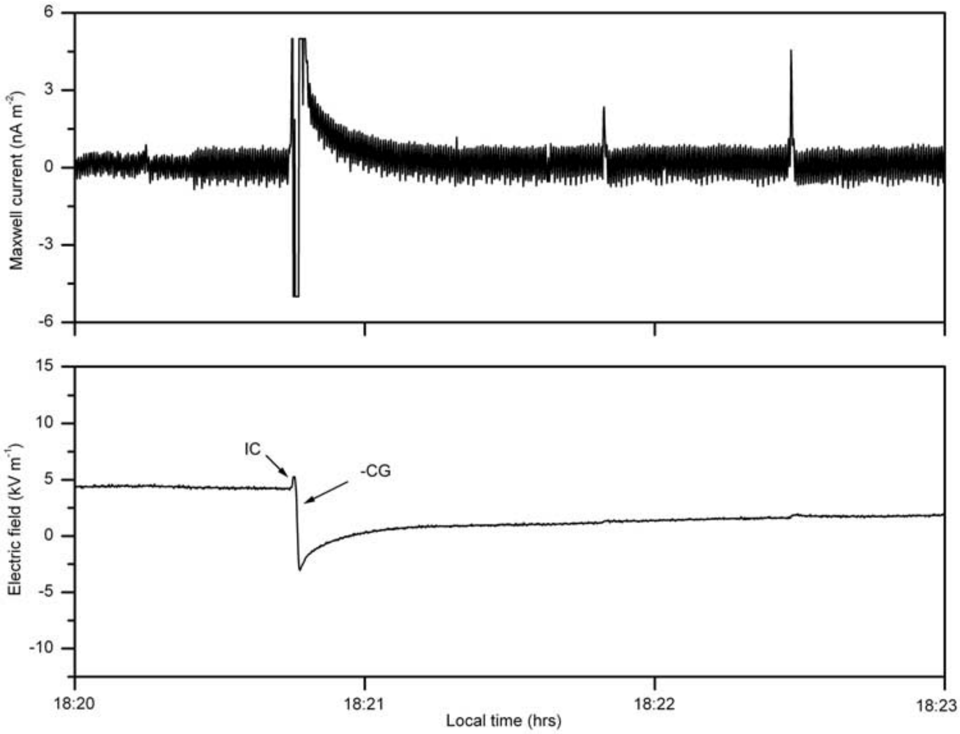

Figure 4. Electric field and Maxwell current changes on an expanded timescale during a typical flash in stage D.

an expanded timescale during a typical flash in this period. The electric field subsequently again increases for 5–20 s at a slower rate before finally decreasing and tending to recover to its predischarge positive value. Out of 13 flashes that occur between 1754 and 1815 h, 10 (C_1, C_2, C_4, C_5, C_6 and C_9 to C_{13}) show such field changes and occur with a periodicity of about 1 to 1.5 min. In contrast with the unipolar transients in the Maxwell current associated with the flashes in stage B, shown in Figure 2, the Maxwell current associated with such flashes in stages C has a bipolar transient whose magnitude generally exceeds the range of our instrument (± 5 nA m^{-2}). These bipolar events will be further discussed in sections 8 and 9.

5.4. Stage D

[17] At 1815 h, the polarity of electric field changes to positive, and the shape of the field changes accompanied with the discharges in this stage also changes. Contrary to the flashes in stage C, the initial positive field change, indicating destruction of positive charge above, is now followed by a much greater negative field change indicating destruction of negative charge above with approximately the same rate of field change (Figure 4). Subsequently, the electric field's exponential recovery either continues or changes its direction after 5–20 s. The average tendency of electric field, from TP1 to TP2 is to decrease and the after-discharge electric field for each flash in stage D generally tends to settle at a value lower than that for the previous flash. Six flashes that occur in the next ~13 min have similar shape and occur, as in stage C, with a periodicity of 1 to 1.5 min. In this stage also, the Maxwell current for each flash has bipolar transient with its magnitude exceeding ± 5 nA m^{-2}.

5.5. Stage E

[18] The electric field in this stage is large and negative and, after a flash, soon recovers to its predischarge level. However, the frequency of lightning and the fluctuations in the Maxwell current considerably decrease. Because of the significantly different after-flash field changes, these flashes deserve to be put in a different category. Although, our observations could not be continued after 1844 h, the thundercloud was observed to dissipate soon after.

6. Anomalous Flashes

[19] It is worth noting that each TP in Figure 1 has one or more anomalous flashes. The field changes during these anomalous flashes are grossly different from those exhibited by the category of flashes in either of their adjacent stages. Figure 5 shows the electric field and Maxwell current changes on an expanded timescale during these flashes. In each of these flashes, (1) the total field change and thus presumably the charge destroyed in it is larger than in most of the other flashes, (2) the initial after-flash field recovery is delayed and is much slower as compared to that of other flashes, (3) the field changes have one/more additional field reversals as compared to that in any other flash of the neighboring stages, and (4) the Maxwell current associated with these flashes unlike simple +CG discharges in stage B, show a positive overshoot. The anomalous flash in TP3 looks as a combination of a flash in stage D followed by a flash in stage C. Above features of the anomalous flashes indicate that either these flashes significantly change the charge distribution in storm so as to change the nature of flashes occurring before and after them, or the charge depositing

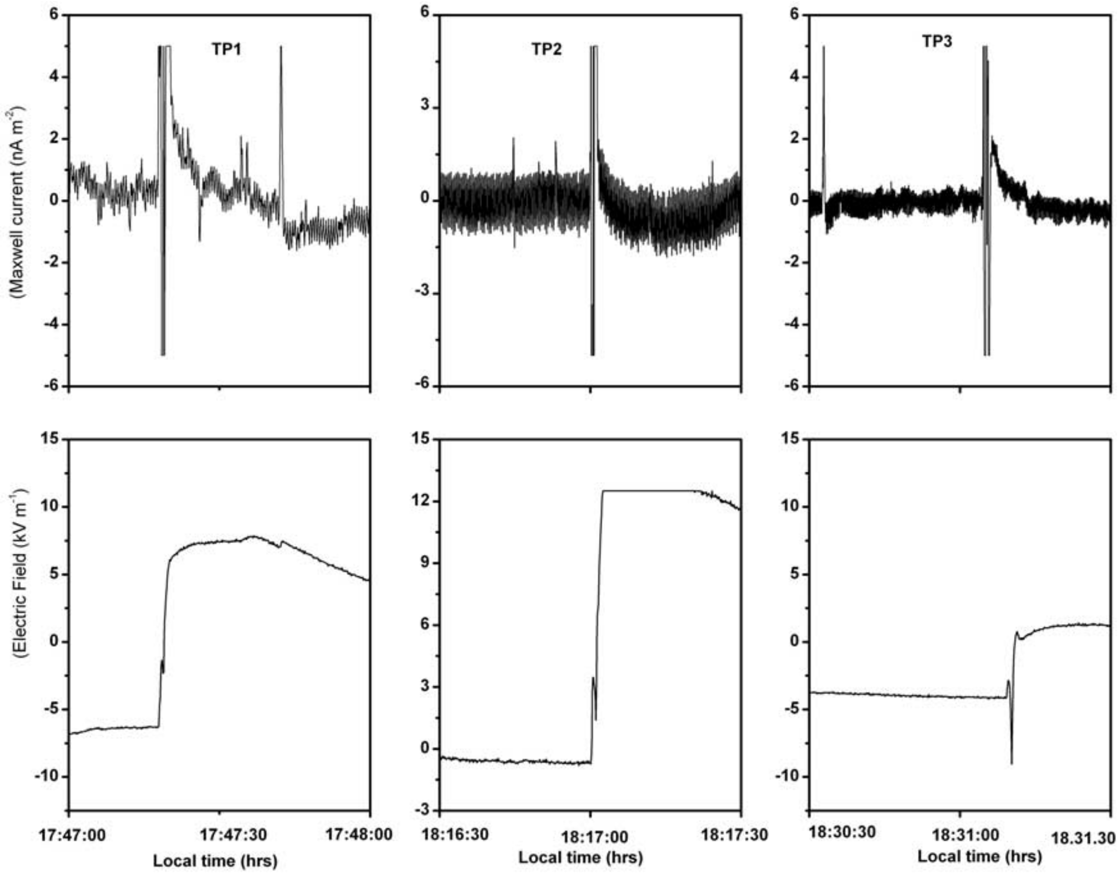

Figure 5. Electric field and Maxwell current changes on an expanded timescale during the flashes in the transition periods TP1, TP2, and TP3.

processes or at least their efficiencies in depositing charge, at different places in storm systematically change as the storm evolves.

7. Maxwell Currents

[20] The Maxwell current significantly varies over different timescales. It consists mostly of displacement current during a lightning discharge and the transients in current quite often exceed ±5 nA m^{-2}. The contribution of precipitation current to the Maxwell current in this case is zero since no precipitation was observed at the observatory throughout the storm period. In stage A, the average value of the Maxwell current is always positive and varies in the range of 0–2 nA m^{-2}. In stage B, it fluctuates from +1 to −2 nA m^{-2}, is mostly negative and has comparatively higher values in the later period. As per the polarity determination criteria of *Deaver and Krider* [1991], positive CG discharges during this period show positive overshoots and intracloud discharges a negative offset in the Maxwell current density from where it subsequently relaxes back to its predischarge value. Average Maxwell current is comparatively large and negative during stage C and drops down to almost zero value in stages D and E.

[21] A unique feature of the Maxwell current associated with the flashes in stages C and D is that it changes its polarity several times during the flash period. In other words, the Maxwell current transients associated with these flashes are bipolar. Almost all multiple-discharge flashes in stages C and D have positive overshoots and the magnitudes of overshoots associated with flashes in stage D are generally larger than those in stage C. These flashes occur almost at a constant frequency of once every 1–1.5 min and have almost constant Maxwell current between the two consecutive flashes. The frequency and magnitude of fluctuations in the Maxwell current are however, larger in stage D than in either stages C or E.

8. Triggering of Lightning by the LPCC

[22] The electric field and Maxwell current changes during a few discharges that occur in stage A are similar to those for negative discharges described by *Deaver and Krider* [1991]. All discharges occurring in the positive electric field of stage B show the destruction of positive charge overhead which may occur either in an IC discharge occurring between the LPCC and the main negative charge, or in a CG discharge lowering positive charge to the ground. So, the electric field and Maxwell current changes occurring during the discharges in this stage are also similar but, as expected, opposite in polarity to those of *Deaver and Krider* [1991].

[23] The behavior of the electric field and Maxwell current changes during a flash in stage C suggest that a +CG discharge occurring between the LPCC and ground is immediately followed by an IC discharge between the

Table 1. Minimum, Maximum, and Average Values of the Electric Field Change Due to Positive and Negative Discharges of Flashes in Different Stages of Thunderstorm[a]

Stage	Number of Flashes	Positive Electric Field Change, kV/m			Negative Electric Field Change, kV/m			Overshoot in Maxwell Current, nAm^{-2}		
		Min	Max	Av	Min	Max	Av	Min	Max	Av
C	10	3.13	12.01	6.65	0.48	4.36	2.57	0.76	7.1	4.44
D	6	0.54	4.12	2.14	3.29	11.34	6.78	6	7.7	7.00
E	2	2.14	2.44	2.29	3.67	4.02	3.84	0.92	1.20	1.06

[a]Here, Min, minimum; Max, maximum; and Av, average.

LPCC and the main negative charge of the thundercloud. Supporting this are the facts that (1) the field change involving destruction of negative charge in the second discharge immediately follows the field change due to the first discharge involving destruction of positive charge and the field change of each polarity spans over a period of a few seconds, thereby indicating that both discharges occur at the same place, (2) the field change associated with the CG discharge is generally much larger than those associated with IC discharge thereby indicating that an IC discharge follows a +CG discharge in this case, and (3) the Maxwell current transient associated with these flashes is bipolar and has a positive overshoot after the flash. On the other hand, the Maxwell current associated with some single-discharge flashes in stage C shows only unipolar transients. These features of flash can be explained if one considers that one discharge triggers another. On the basis of these facts we hypothesis that the +CG discharge triggers an IC discharge. This is quite plausible in view of *Wilson*'s [1956] suggestion that the removal of lower positive charge will serve to increase the electric field between the upper positive and main negative charge, thereby promoting the subsequent IC discharge. The possibility that both positive and negative field changes are associated with the stroke or interstroke processes of a single discharge can be ruled out as such changes occur over a fraction of a second as compared to a period of a few seconds over which each of the positive and negative field change spans in the present observations. The initial increase for 5–20 s in the recovery curves of the electric field indicates a higher rate of growth of main negative charge as compared to LPC of the thundercloud. A similar conclusion was drawn by *Pawar and Kamra* [2002] from the recovery curves of lightning flashes from an overhead thunderstorm.

[24] The electric field and Maxwell current changes observed during any flash in stage D suggest that, contrary to the flashes in stage C, an IC discharge occurring between the LPCC and main negative charge is immediately followed by a −CG discharge occurring between the main negative charge center and the ground. In stage D, the field change associated with the first discharge is smaller than that associated with the second discharge. On the basis of similar facts as in stage C, it is hypothesized that in this case, an IC discharge may trigger a −CG discharge. The change in field level at which the recovery curve of each subsequent flash in stage D tends to settle, indicates the growing effects of the downward transport of main positive charge and the LPCC on the surface electric field. Such downward transport of positive charge may eventually lead to the end-of-storm-oscillation in the dissipating stage of the thundercloud as discussed by *Moore and Vonnegut* [1977].

[25] Flashes E_1 and E_2, in our records, are not much different from those in stage D except that the field remains large, positive and almost unchanged before and after a flash. The Maxwell currents associated with these discharges, as with all other discharges where the positive and negative field changes are small and nearly equal, have comparatively small overshoots of <1 nA m^{-2}.

[26] Most flashes in stages C, D and E consist of two discharges: one showing the positive and the other negative field change. Table 1 shows the minimum, maximum and average values of the positive and negative electric field changes due to the first and second discharges of a flash and of the overshoots associated with them in different stages of the thundercloud. The average ratio of the positive to negative field change due to the two discharges of a single flash decreases from 2.56 in stage C to 0.31 in stage D. The extrapolated values of overshoots are larger for flashes in stage D where the field goes more strongly negative (toward fair weather polarity) than in stage C. Even within stage D the overshoots are larger for flashes where the after-discharge field values change their polarity to the fair-weather one.

9. Discussion

[27] Our observations can be interpreted in terms of a tripole structure with a widespread LPCC in the base of thundercloud. Large spatial and temporal scales of the LPCC are supported by the fact that for more than 60% of the duration of storm the surface electric field remains strong and negative. The early observations of *Banerji* [1930, 1932] made under similar thunderstorms occurring in the premonsoon seasons near this region further support the existence of positive charge spread over large areas in the bases of thunderstorms. Therefore we interpret our data assuming a tripolar charge structure, but other interpretations based on a different charge structure could fit the data as well as from the assumption of a tripole structure. The LPCC in this thundercloud seems to play a dominant role not only in initiating but also in triggering an intracloud/cloud-to-ground lightning discharge. Unusually large number of +CG flashes from this thunderstorm may perhaps be linked to the proximity of the LPCC to ground. The systematic change in the role of the LPCC from initiating a + CG discharge between the LPCC and ground which triggers an IC discharge between the LPCC and the main negative charge center to initiating an IC discharge between the LPCC and the main negative charge center which triggers a −CG between the main negative charge center and the ground seems to be well illustrated in our observations in stages C and D.

[28] Our observations provide an excellent data set to follow the evolution of lightning in this thundercloud. The gross charge distribution in this thundercloud seems to undergo slow but systematic changes with time. On the basis of the surface observations of the electric field and Maxwell current and supported by some visual observations, we propose below the following systematic evolution of lightning in this thundercloud. In the initial stages of the thundercloud, when its vertical growth is rapid, a positive dipole develops and a few intracloud discharges occur between the main positive and negative charge centers of the cloud [*Krehbiel*, 1986]. The Maxwell current is mostly positive during this period. Within $\sim$15 min of the development of cloud, the LPCC develops and reverses the polarity of the surface electric field to negative. The LPCC actively participates in causing both IC and CG discharges. Consequently, there is considerable increase in the frequency of both IC and simple one-stroke +CG discharges destroying positive charge in the LPCC. The flash rate increases from 0.4 in stage A to 1.5 flashes min^{-1} in stage B. Subsequently, it decreases to 0.6, 0.5 and 0.2 flashes min^{-1} in stages C, D and E, respectively. Thus the maximum flash rate exhibited by this thunderstorm appears to be well below the flash rate in Florida storms [*Krider and Musser*, 1982; *Deaver and Krider*, 1991] and also the global mean rate of about 3 flashes min^{-1} [*Williams*, 2001]. Further, this flash rate is about 2 orders of magnitude lower than the one reported by *Rust and MacGorman* [2002] in STEPS storms. It need be noted that unlike the present storm, Florida storms are most frequently characterized by foul weather field between flashes, particularly in the developing through matured stages. The STEPS storms are supercell structures with much larger dimensions in space and time as compared to this storm. Therefore the differences in flash rates as stated above, are of significance in view of the tripolar structure, with such dominant LPCC in this storm. These differences in flash rates are also important in view of some reports of observing such low flash rates in the storms that occur over water bodies (e.g., E. R. Williams, personal communication, 2003). However, more data are needed to establish the typical behavior of such storms occurring in this region. Further investigations are also required to study the transport of marine aerosols to this region in different seasons and to assess the maritime influences on microphysical, dynamical and electrical characteristics of the clouds as pointed out by *Williams et al.* [2002]. Possibility of such an influence on this storm cannot be ruled out in view of the solar radiometric observations of *Devara et al.* [2002] that the contribution of large aerosol particles to the columnar aerosol optical depth at this station increases for the month of May, just before the onset of the southwest monsoon season which is normally 10 June for this region. Aerosol optical depths for other seasons in this region are typical of urban environment. Added to this, the fact that the thunderstorms developing in this region in the premonsoon season are generally stationary or show little east-to-west movement, indicates that these storms develop because of the local convection of continental air and may have, if any, only a weak maritime influence.

[29] The Maxwell current slowly changes to negative in stage B and +CG discharges have negative overshoots. Such IC and CG discharges actively continue to occur for $\sim$53 min until some anomalous discharges occur in TP1 that seem to considerably change the charge distribution in the cloud. The change in polarity of current overshoots associated with these anomalous flashes indicates a change in charge distribution in thunderclouds. In modified distribution of charge in the thundercloud +CG discharges trigger intracloud discharges. The significant increase in the negative Maxwell current after the discharge at 1745 and other discharges in TP1 is noteworthy in this respect. Figure 6 illustrates that the difference in the Maxwell current and displacement current calculated from our field records significantly changes after the occurrence of these discharges. The Maxwell current is the sum of the components due to the conduction, convection, lightning and displacement currents. The contribution due to the lightning current is zero between two consecutive discharges. Therefore the increasing difference in the Maxwell current and displacement current in Figure 6 indicates that a significant amount of charge is being transported by the conduction and convection processes during this time. A significant change in the Maxwell current is again noticed after the flash C13 and the anomalous flash in TP2. This change in the Maxwell current, perhaps, again leads to a change in the charge distribution that causes a change in the sequence of discharges in the flashes that occur in stage D.

[30] An outstanding feature of this thunderstorm's electrification is that most of the flashes within a single stage produce, as a group, almost similar changes in the surface electric field and Maxwell current. The observation strongly indicates that the charge distribution in the thundercloud remains much the same during the particular stage. These stages are sharply separated from each other by one or two anomalous flashes. Thus the charge transfer caused by these anomalous flashes may modify the thundercloud charge distribution in such a way that the type of lightning produced thereafter changes. Alternatively and perhaps more likely, these anomalous flashes reflect the response of lightning to the change in charging behavior of the cloud. So, subsequent to the anomalous flashes, the charging of the cloud evolves in such a way as to cause the changes in the nature of lightning. The latter alternative is supported by *Williams and Boccippio* [1993].

[31] The sequence of discharges in a flash in stage D demonstrates how the growth of LPCC can lower the positive surface field produced by the main negative charge of the cloud. The occurrence of an intracloud discharge in this stage will destroy the positive charge in the LPCC, unshield main negative charge and soon afterward momentarily increase the positive field at the ground. Our observations confirm such field enhancement after IC discharge in all flashes in stage D.

[32] Almost constant frequency of flashes in stages C and D suggests that a constant charging current flows in the thundercloud. Observations of almost constant Maxwell current in our measurements in stage D support such inference.

[33] Irrespective of the polarity of CG discharge and whether it precedes (as in stage C) or follows (as in stage D) IC discharge, the Maxwell current always has a positive overshoot and the electric field always increases for the initial 5–20 s after each flash in stages C and D. This observation suggests that the charge centers involved in

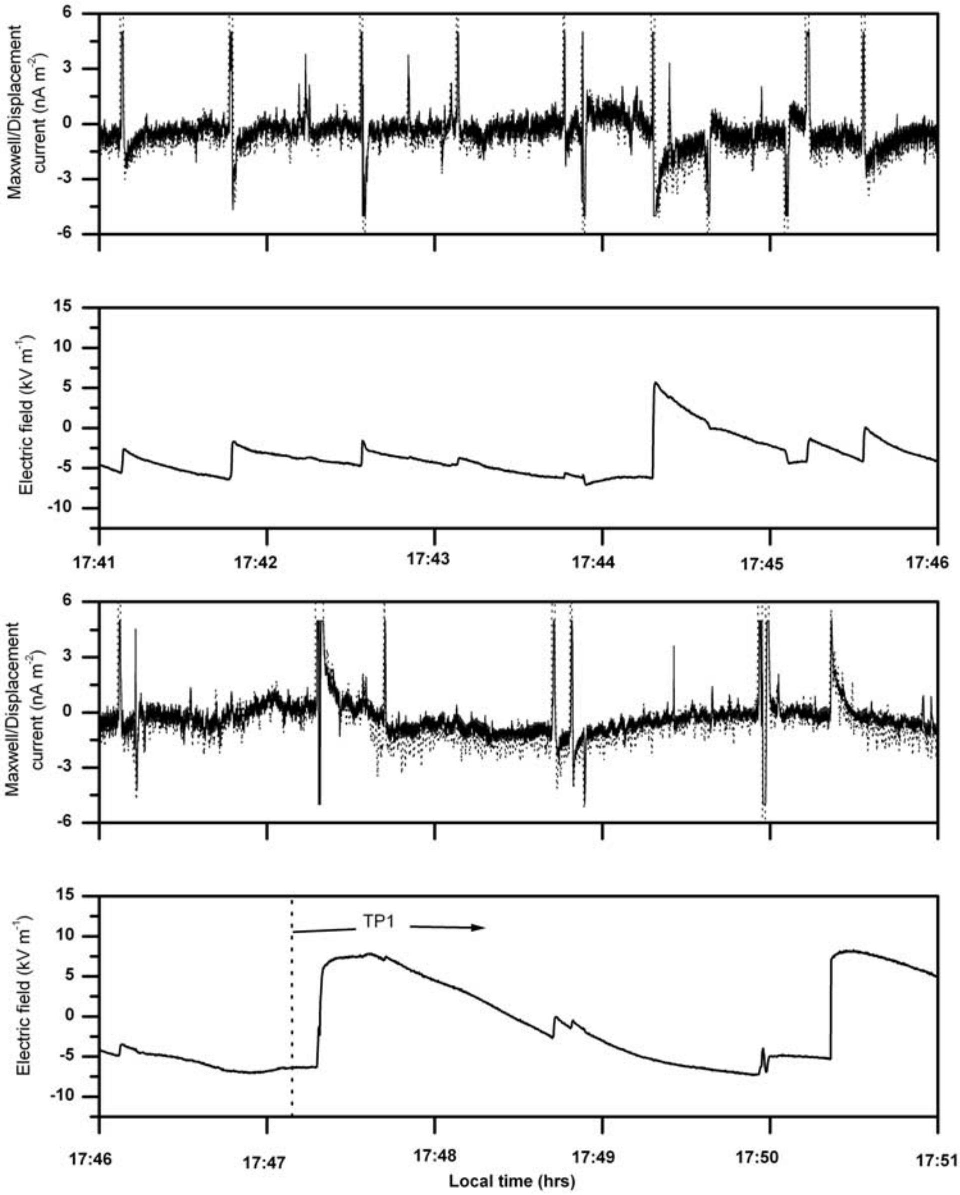

Figure 6. Electric field, Maxwell current (solid line), and the computed values of displacement current (dashed line) just before and during TP1.

each flash, whether in stage C or D, are the same and the charge distributions resulting after each flash are similar in both stages. The time duration (shown by T1 in Figure 3) for the overshoot to recover back to its predischarge value is roughly the same (5–20 s) in which the electric field grows before decreasing or settling to a nearly constant value. These simultaneous changes in the electric field and Maxwell current indicate that the conduction current and/or displacement current components dominate the Maxwell current during this period. After this period, the Maxwell current remains almost constant irrespective of changes in electric field, until the next flash occurs. So, during this period, the convection current component, which includes precipitation currents, will mainly contribute to the Maxwell current. From such observations, *Krider and Musser* [1982] concluded that the cloud electrification processes may be determined by the meteorological processes in the thundercloud.

[34] The magnitude of the overshoot following a flash in stages C and D seems to depend upon the relative magnitudes of field changes caused by the IC and CG discharges in a flash. Unfortunately, our measurements of the Maxwell current were limited to a range of ±5 nA m^{-2}. The overshoots in stages C and D often exceeded these limits. However, we have estimated the magnitudes of overshoots by extrapolating some Maxwell current expanded-time records and found them to increase with the ratio of field changes in the CG and IC discharges of each flash. Average magnitude of overshoots increases from ~3.3 nA m^{-2} in stage C to ~7.3 nA m^{-2} in stage D.

[35] An IC discharge neutralizes equal and opposite charges and leaves the cloud as neutral or with the same net charge afterward, as before the discharge. On the other hand, a CG discharge transfers one polarity of charge from the cloud to ground and thereby leaves the cloud with a net

charge of opposite polarity. Therefore, after a CG discharge, the cloud will attract ions of opposite polarity from its surrounding clean air. Flow of these ions toward cloud will constitute a conduction current flowing to the cloud. To keep the total current flowing through a vertical column of the atmosphere as constant with altitude, the additional conduction current flowing to the cloud as a result of a CG discharge will enhance the electric field and the rate of field change at the ground. Consequently, the conduction and/or displacement current at the ground will increase and this increase may be reflected in the overshoot in Maxwell current. Opposite polarities of the overshoots associated with +CG and −CG discharges may result because of the opposite polarities of the net charge with which the cloud is left with after these discharges. The reversal in polarity of point discharge currents at the before- and after-discharge electric fields may further contribute to overshoots if these field values are larger than corona threshold. After a CG discharge, the change in electric field will be proportional to the conduction current flowing to the cloud, which should vary exponentially with time. Since the Maxwell current after a CG discharge is the sum of displacement current and conduction current, it may vary in a quasi-exponential fashion.

[36] Several mechanisms have been proposed for the origin of charge in the LPCC. One such mechanism proposes that the LPCC might have been caused by the accumulation of positive space charge caused by the positive coronae ions produced at the ground. However, in this case, since large negative fields persist on the ground for most of the duration of the storm, the corona ions produced on the ground will be of opposite polarity to cause or maintain the LPCC. In view of the persistence of the LPCC for most of the thundercloud period in our observations, the charge reversal microphysics related to collisions between ice crystals and graupel particles [e.g., *Reynolds and Neill*, 1955; *Takahashi*, 1978; *Jayaratne et al.*, 1983] as discussed by *Williams* [1989] stands as a strong candidate for charge generation in the LPCC. However, the acceptance of such an explanation in this case needs to be supplemented with the observation that sufficient concentrations of ice crystals exist in the lower part of the mixed-phase cloud.

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